The Theory of Advance of Glaciers in response to Earthquake shaking[1].

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Characteristics of the Yakutat Bay Glaciers. The Alaskan glaciers are, in general, in a state of recession from more advanced positions, though there are some notable exceptions, the most remarkable being some of those in the Yakutat Bay Region. This region, which is situated in the western, or seaward portion of the St. Elias Mountains, is the center of the largest glaciers in North America. The mountains are lofty, some of the peaks rising to elevations of 4000 to 5000 metres; they face a warm sea from which the winds prevail; and consequently they are the seat of heavy precipitation, most of

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This theory was proposed as a result of comparative observations on the condition of the Yakutat Bay glaciers in 1905 and 1906, and some further facts of importance were observed in 1909. In 1905 Prof. Lawrence Martin was associated with me as assistant; and he shared with me in the leadership of the expedition of 1909. I wish to acknowledge his material aid in the development of the theory, and especially in observation of some of the facts on which it is based. The expeditions of 1905 and 1906 were a part of the work of the Alaskan Division of the U. S. Geological Survey, and that of 1909 was under the auspices of the National Geographic Society, as the first of its newly established research expeditions.

Other papers relating to this subject are as follows: Tarr, R. S., Second Expedition to Yakutat Bay, Alaska. Bull. Geog. Soc., Philadelphia, Vol. 5., Jan. 1907, pp. 1—14; Recent Advance of Glaciers in the Yakutat Bay Region, Alaska. Bull. Geol. Soc. America, vol. 18, 1907, pp. 257—286; The Yakutat Bay Region: Physiography and Glacial Geology, Professional Paper, No. 64, U. S. Geological Survey, Washington, 1909, pp. 1—144; also Tarr, R. S., and Martin, L., The National Geographic Society's Alaskan Expedition of 1909, National Geog. Mag. Vol. XXI, 1910, pp. 1—54; Recent Changes of Level in the Yakutat Bay Region, Alaska. Bull. Geol. Soc. America, vol. 17, 1906, pp. 29—64; The Earthquakes of Yakutat Bay, Sept. 1899, forthcoming Professional Paper, U. S. Geol. Survey (in press); Alaskan Glacier Studies, Vol. 1: The Glaciers of Yakutat Bay: to be published by the National Geographic Society, Washington (in preparation).

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Fig. 1. Sketch Map of the Yakutat Bay Region based on the Alaska Boundary Tribunal Map. The newly crevassed glaciers are indicated by broken lines. Scale 1 : 700000.

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which, above an elevation of 600 or 700 metres, falls as snow (Fig. 1). The snow line lies from 600 to 900 metres above sea level, according to exposure and distance from the sea.

From the vast snowfields in these lofty mountains a multitude of glaciers descend, and among them are many different kinds. Some are very small and hundreds of them are as large, or larger, than the best known Alpine glaciers. Three glaciers, the Turner, Nunatak, and Hubbard are great ice streams, crevassed from side to side, and terminating in tidal ice cliffs, from 60 to 90 metres high, from which icebergs are being almost constantly discharged. Other glaciers reach almost or quite to sea level, but, instead of entering the sea, spread out at the mountain base in broad ice fans, or bulbs, in which the ice is nearly or quite stagnant. In some cases two or more glaciers unite at the mountain base, forming a more extensive area of stagnant ice, to which Prof. Russell gave the name piedmont glacier. Malaspina Glacier is the type and largest known example of the piedmont glacier, and it is fed by several very large glaciers from the St. Elias Mountains, as well as by numerous smaller ones. There are other smaller examples of piedmont glacier in the neighborhood.

Both the piedmont glaciers and the expanded piedmont ice bulbs receive so little ice, and in some cases none at all, that the ice in them is either motionless or moving with extreme slowness. Terminating, as they do, in a cool, damp temperate climate near sea level these stagnant outer portions of the glaciers have so wasted by ablation that they are partly, and in some cases completely covered by extensive sheets of moraine to which I have applied the name ablation moraine[1]). In places the ablation moraine is so thick, and the ice upon which it rests is so motionless, that vegetation finds a foothold; and in places dense alder thickets grow, and even forests of spruce and cottonwood.

In 1905 the glaciers of the Yakutat Bay Region were, in general, in a state of recession, thus harmonizing with most of the Alaskan glaciers. One glacier, the Galiano, had been subjected to an impulse by which an alder thicket, that grew on its piedmont bulb when observed by Russell in 1890 and 1891, had been destroyed; the Hubbard and Turner glaciers had undergone minor changes in the position of their fronts; and it is possible that some of the smaller glaciers had undergone an advance similar to that of the Galiano

[1]) Tarr, R. S., Some Phenomena of the glacier Margins in the Yakutat Bay Region, Alaska. Zeitschrift für Gletscherkunde, III. Band, 1908, pp. 55—88.

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glacier, though of this the evidence is not convincing. Otherwise recession was in progress, and between Dr. Gilbert's study of 1899 and ours of 1905, there had been notable recession in some of the largest glaciers, while there was physiographic evidence of convincing nature that these same glaciers, and others, had been receding for a long time before Gilbert's study in 1899, or even of Russell's in 1890/1. In 1906, however, there began a series of advances of remarkable character, the nature of which is outlined in the next section.

Advance of Glaciers 1906—1909. In June 1906 four glaciers were found to be in a wholly different condition from that in which they were ten months earlier, in August 1905. One of these, Haenke Glacier, is a valley glacier, comparable with the largest Alpine glaciers, which in 1905 terminated within its mountain valley, near sea level, on an alluvial fan that its glacial streams had built in front of it. The glacier surface was covered with moraine, and in August 1905 no crevasses were visible in it. When next seen, in June 1906, the front of the glacier had been pushed forward 1.5 or 1.6 km., the glacier had completely overridden its alluvial fan, and its end was now tidal (Fig. 7). Accompanying this advance was a profound breaking of the ice, and a great thickening of the lower end.

A second advancing glacier was the Variegated, a valley glacier comparable to the Aletsch in size and condition, but expanding beyond the mountain base into a broad, stagnant, moraine-covered piedmont bulb. In August 1905 we walked freely over the stagnant bulb, and for several miles up the valley glacier, everywhere finding the surface easy to traverse, and nowhere encountering difficult crevassing. In June 1906 the glacier was absolutely transformed. The valley portion, where we had so easily walked ten months earlier, was now a sea of crevasses and utterly impassable, and the crevassing had extended far out into the hitherto stagnant moraine-covered bulb. Accompanying the breaking was a lateral spreading of the glacier, both in its mountain valley and in the piedmont bulb, and a great thickening in all the outer portion. There was also some advance, but not nearly so much as in the Haenke glacier, the energy of the advance apparently being dissipated in thickening and breaking the expanded piedmont bulb.

Similar change was observed in the third advancing glacier, the Atrevida. This is also a glacier of moderate size and not one of first rank, or even of second rank, among the Yakutat Bay glaciers.

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Its valley portion is covered with ablation moraine, and its expanded piedmont bulb, which coalesces with its neighbor to the west, the Lucia Glacier, forming a small piedmont glacier, is also moraine covered, and on its outer portion bears a forest of alder, cottonwood and spruce. In August 1905 we walked freely over this surface (Fig. 2), but in June 1906 both the valley portion and a large part of the piedmont bulb were so completely broken that we could not possibly cross the glacier (Figs. 3 and 9). Here, too, there was a lateral

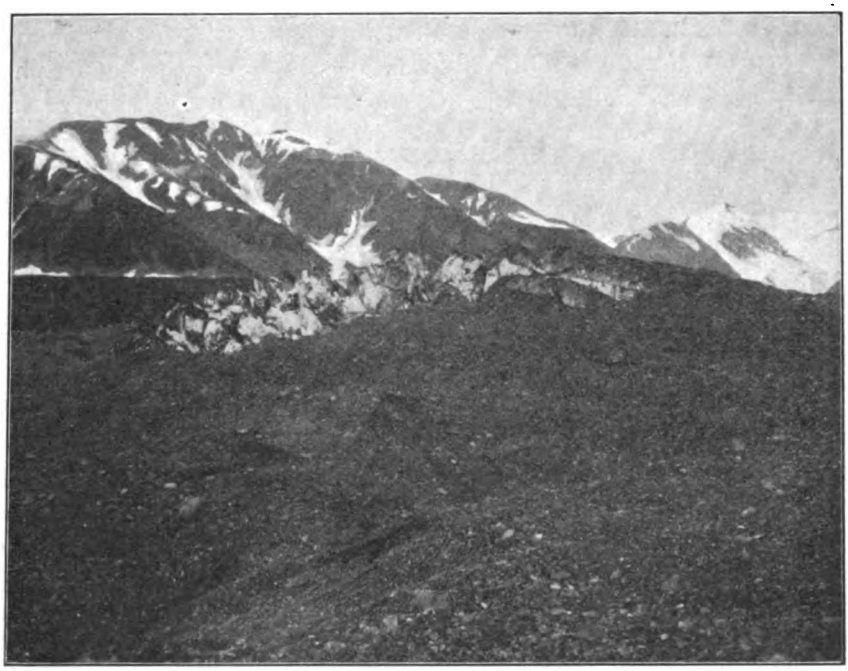

Fig. 2. The moraine-covered surface of Atrevida Glacier, August 1905, showing the only area of crevassing observed in 1905, probably the first stage in the great advance of 1906; see Figures 3 and 9, p. 7 and 29.

spreading and a notable thickening of the glacier, which along the eastern margin was advancing into the fringing forest. It is possible that in this glacier the advance of 1906 was just beginning in the summer of 1905, for on its moraine-covered surface there was a dome of crevassed ice (Fig. 2) which we now interpret as the first sign of the coming advance. It was actively advancing in the summer of 1906.

The fourth advancing glacier of the 1906 series is the Marvine Glacier, which is much larger than either of the others. This glacier.

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on emerging from its mountain valley, spreads out at the mountain base and contributes the ice of which the eastern lobe of Malaspina Glacier is made. Russell crossed it at the valley mouth in 1890, and he crossed the outer portion of the Marvine lobe of the Malaspina Glacier in 1891; while Abruzzi and Bryant crossed it in 1897. In these years the eastern, or Marvine, lobe of the Malaspina was so smooth that sledges were easily drawn over its surface. As we looked down upon it in August 1905 it was evidently in the same condition; but in June 1906 the Marvine Glacier and its continuation, the Marvine lobe of Malaspina Glacier, was broken into impassable condition from as far within the mountain valley as we could see, to the periphery of the piedmont glacier near the sea. An area of ice fully 24 kilometres long, and from 13 to 15 kilometres broad in the broadest part, was transformed from smooth surface to a sea of crevasses. Advance was actively in progress along the margin of the Malaspina and by it the forest growth in the ablation moraine was being destroyed, while the broken ice was being thrust forward into the fringing forest. This forest-covered margin, which had been stagnant and quite motionless for fully half a century, was suddenly given such activity that its condition resembled that of a broken ice fall in a glacier.

Between 1906 and 1909 one of the larger glaciers of the region, the Hidden, passed through a similar period of advance. In 1905, and when last seen late in June 1906, this glacier was smooth and uncrevassed (Fig. 4), and it had been receding rapidly since observed by Gilbert in 1899, and probably for many years before that date. Early in July 1909, when we next saw this glacier, its front had advanced about 3¼ kilometres, and where the ice front stood in 1905 the depth of the glacier was 340 metres (Fig. 5). At the same time the hitherto smooth surface of the glacier had been greatly broken, as the other advancing glaciers had been. In this glacier, as in the Haenke, the energy of the advance was not dissipated in an expanded piedmont bulb, for the glacier terminus was within a mountain-walled valley; hence the thrust of the transformed glacier was expended in a forward movement of the terminus, not in the breaking, thickening, and spreading of a piedmont bulb. We are unable to assign an exact date for the advance of the Hidden Glacier. We know that it occurred between late June 1906 and early July 1909, and we infer that it took place either late in 1906 or in 1907. This inference is based upon several considerations, the most important being the extent to which ablation had healed the broken surface

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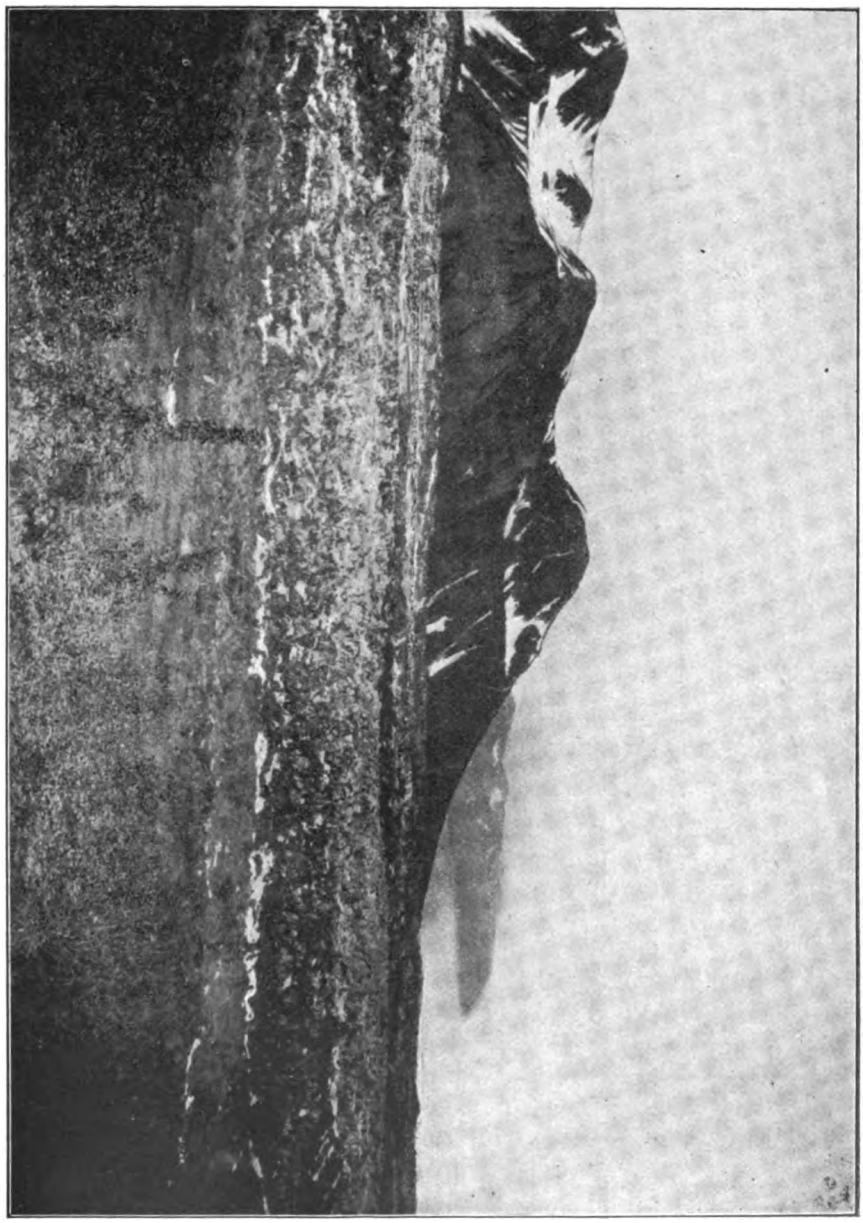

Fig. 3. Atrevida Glacier surface, impassably crevassed, July 1906. Contrast this crevassed surface with that of 1905, as shown in Fig. 2. The site of Fig. 2 is about in the middle of this picture.

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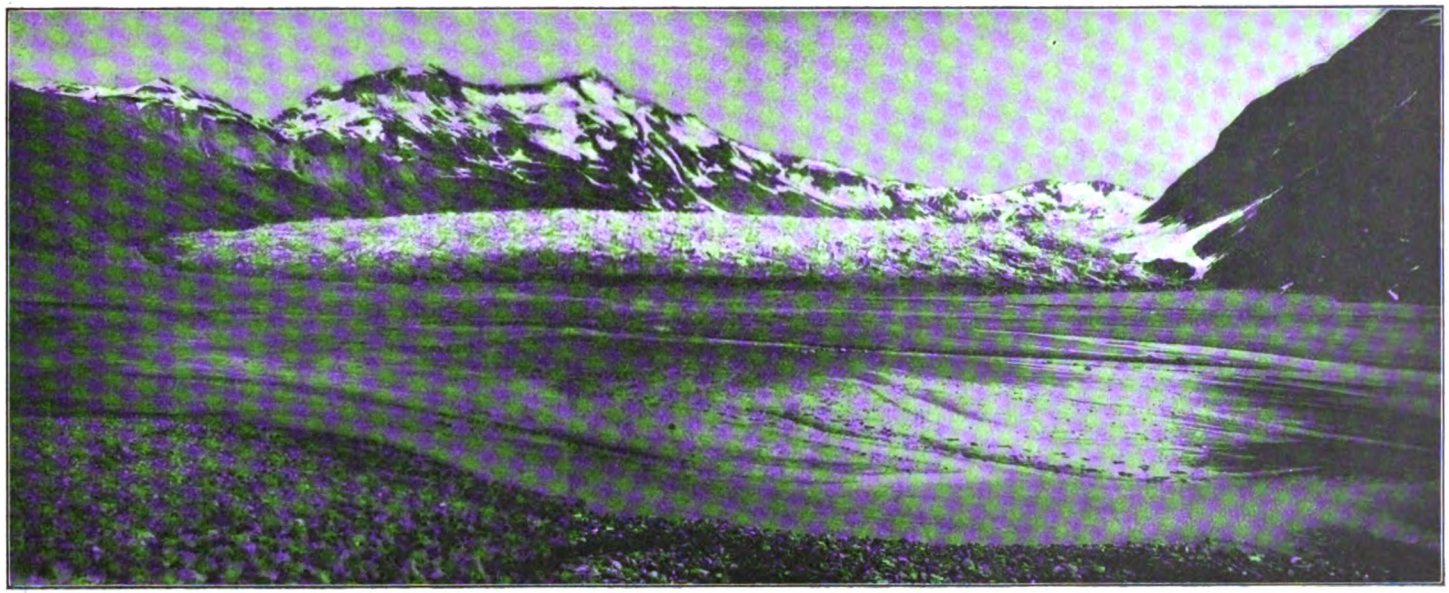

Fig. 5. Hidden Glacier, July 1909, from same site as Fig. 4. The ice front is $3\,^1/_4$ kilometers nearer than in 1906, and where the front stoud then, the ice now has a depth of 430 m.

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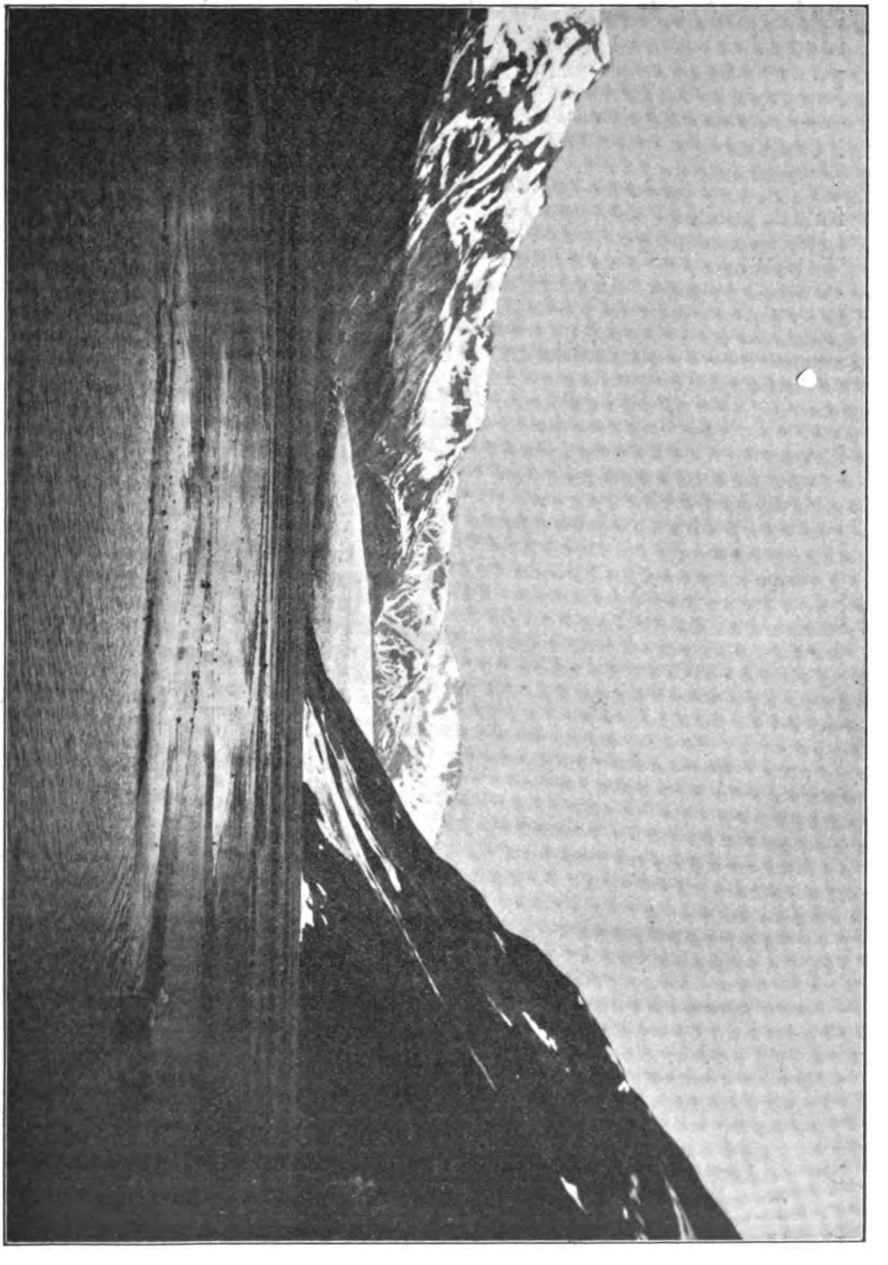

Fig. 4. Smooth, uncrevassed surface of Hidden Glacier, June 1906. Compare with Fig. 5.

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since the advance; for by July 1909 we could walk over the broken surface, though only by the exercise of caution, and by much roundabout travel to avoid the abundant crevasses. Such healing by ablation surely required one full season (1908) and probably more: hence we assume the date of advance to have been in 1907, or possibly late in 1906.

During the National Geographic Society Expedition of 1909 we found Lucia Glacier in an early stage of advance (Fig. 8), but still so broken that it was impassable where we had easily crossed it in 1905 and 1906. Here there was notable spreading of the margin of the glacier, and the breaking of the surface extended far out into the moraine-covered piedmont bulb which, as already stated, coalesces with that of Atrevida Glacier.

Among the Yakutat Bay Glaciers there are some in which we have no evidence of advance. Some of the smaller of these may have advanced before 1905, and have so healed by ablation by that time that we failed to recognize the evidence of advance. This would not be remarkable, since we have no previous knowledge of their condition, and since ablation proceeds rapidly in this climate, and, with the aid of the heavy moraine cover, would soon mask the evidence of advance. Had we not had Russell's description and photographs of the condition of Galiano Glacier in 1890 and 1891 we probably would not have detected evidence of its advance. But while it is possible that we have failed to find evidence of advance in some of the small glaciers that may have advanced, there are some that have surely not undergone change analogous to those described above. This is true, for instance, of the small Black Glacier which extends to the end of its mountain valley close by Galiano Glacier. It is also true of some of the larger glaciers, notably Fourth Glacier and Nunatak Glacier in Yakutat Bay, and some of the tributaries of Malaspina Glacier, such as Hayden and Seward Glaciers. Turner and Hubbard glaciers have suffered slight advance which may be minor movements analogous to those of the glaciers whose transformation has been so great; and in 1909 an advance began in the eastern portion of Hubbard Glacier which may be the beginning of a more pronounced advance in that great glacier.

The observations of the expeditions of 1905, 1906 and 1909 prove that in seven glaciers a long period of stagnation and recession was abruptly terminated, stagnation being replaced by great activity, and recession by advance. This change in condition has affected glaciers

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of greatly different kinds, some being small with few tributaries, some large with many tributaries. There is a rough agreement between size of glacier and time of occurrence of the period of advance. The smallest of the advancing glaciers, the Galiano, underwent its transformation before our first visit and probably in 1900 or 1901; in 1906 a group of three glaciers of about the same size — the Variegated, Haenke and Atrevida — were advancing; in 1907, or thereabouts, a larger glacier, the Hidden advanced; and in 1909 the large Lucia Glacier, and perhaps also the Hubbard, began to advance. Marvine Glacier is the one apparent exception to this order of progression, for it is a much larger glacier than the other advancing glaciers of the 1906 series; but we know almost nothing about its length and the condition in its reservoir or its tributaries. There may be some peculiar conditions in its unknown portion to account for its early advance. None of the largest glaciers of the region, the tidal Turner, Nunatak[1]) and Hubbard glaciers, have as yet responded to the cause which has led up to the remarkable transformation of so many of the Yakutat Bay Glaciers; and some of the larger nontidal glaciers, like the Fourth, Hayden and Seward Glaciers, have also failed to respond.

Our observations of 1909 prove, what was previously suspected from the behavior of Galiano Glacier, that the advance is not only spasmodic, but that its termination is equally abrupt. Within a period of a year, or thereabouts, the complete cycle is run. None of the four advancing glaciers of the 1906 series continued to advance long after the period of our observation. Their advancing margins of 1906 are about where they were then observed to be, and by 1909 the broken surfaces of the glaciers were so healed by ablation that we could again travel over them. Thus, in 1909, we travelled over both the Variegated and Atrevida glaciers (Fig. 6), which were impassable in 1906: but their surfaces had by no means returned to the smooth condition of 1905. Hidden Glacier had advanced, thickened and become greatly broken, and its surface had been reduced by ablation to passable condition between June 1906 and July 1909. The history in all cases has been the same: an abrupt, spasmodic advance with accompanying breaking of the surface, a brief period of but a few months of this condition, then cessation of advance and return to

[1]) Prof. Lawrence Martin, who has visited Yakutat Bay in 1910 reports an advance of Nunatak Glacier of over 300 meters in the interval between August 1909 and June 1910.

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stagnation, with subsequent healing of the broken surface by ablation. The largest portion of the cycle, from unbroken stagnant condition to advance with accompanying breaking, and back to the same condition, is that of the healing of the broken surface by ablation, which requires a period of several years.

That seven glaciers in a single district should undergo such notable advance and transformation as those in the Yakutat Bay region have done is certainly a remarkable phenomenon, and, so far as I know, without parallel. It is noteworthy, too, that so far as our records show, the advance is confined to the region in and near Yakutat Bay. Some of the Alaskan glaciers in other districts are advancing, notably Columbia Glacier in Prince William Sound; but the advance is of a different order from that of the Yakutat Bay glaciers: it is less spasmodic and less spectacular. Neither to the northeast nor to the southeast of Yakutat Bay are there any records of advancing glaciers which can be compared with those of Yakutat Bay.

Consideration of Alternate Hypothesis. To account for such localized, intensive and spasmodic advance of glaciers presents a problem of interest and importance, to the solution of which I have naturally given much attention. Various hypothesis have been considered, most of which are easily eliminated because incapable of explaining the facts. Such, for instance, are the hypotheses of uplift of the mountains, or tilting of the valleys, both of which fail in important respects aside from the absence of evidence of uplift or tilting, and of their general improbability. Absolutely fatal to either of these hypotheses is the fact that the advance ceased as abruptly as it began, which could not have been the case if the advance was due to either elevation of the mountains or tilting of the valleys. Another hypothesis easily eliminated is that the phenomenon is due, either directly or indirectly, to breaking of the glaciers by earthquake shaking; for such a cause does not explain the advance and thickening of the glaciers.

It is less easy to eliminate the hypothesis of advance as a result of climatic variation, for we have little knowledge concerning the variation in precipitation in the Alaskan Coast Ranges. Such data as we have from stations at sea level proves a considerable difference in precipitation from place to place, and, at the same station, from year to year. We may fairly assume, therefore, that there are important variations in the amount of snowfall at a given place among

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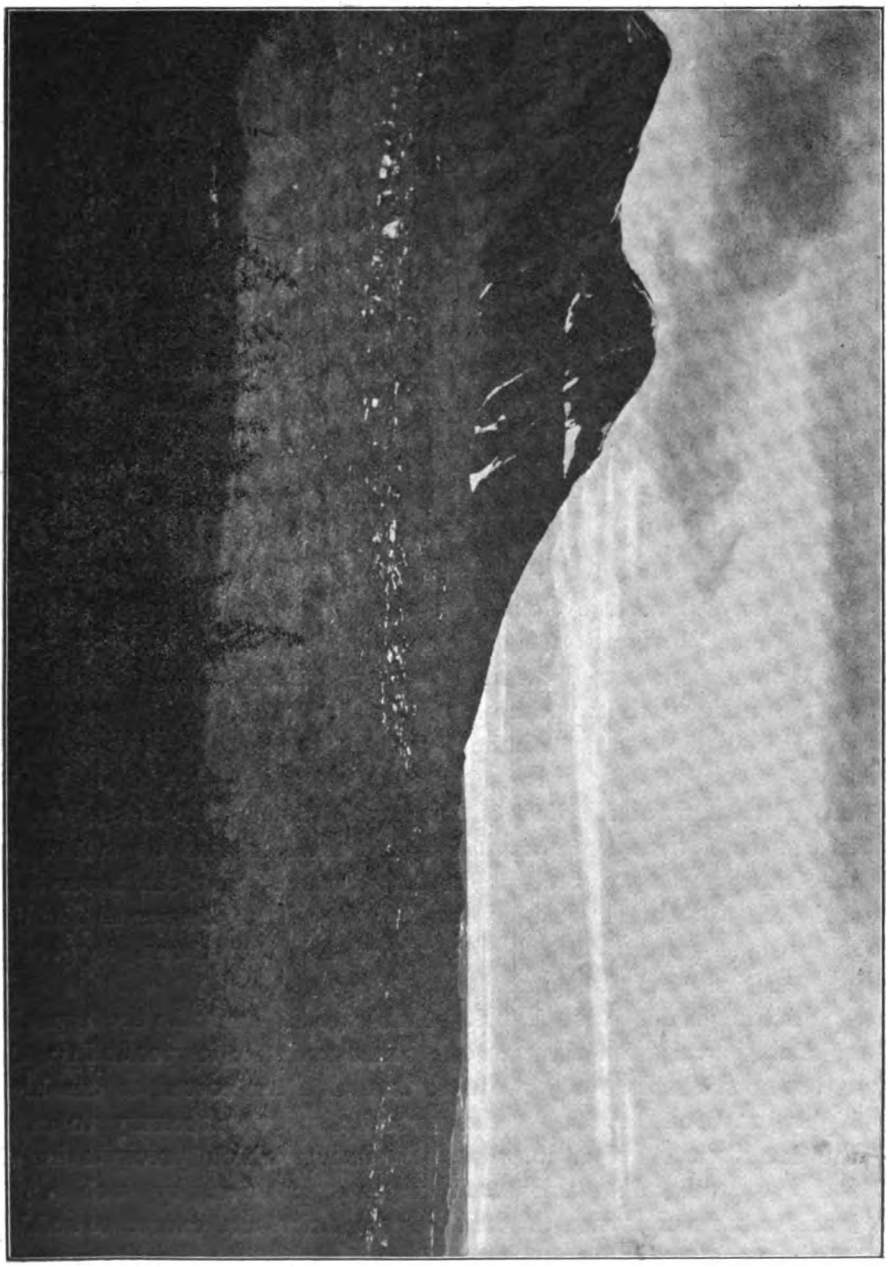

Fig. 6. Atrevida Glacier, July 1909, from same site as Fig. 3. The advance has ceased, and the broken surface of 1906 is healed by ablation, approaching the 1905 condition, though much rougher.

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the mountains, and that while one section is experiencing unusually heavy precipitation another may be receiving less than normal. Granting, however, the maximum amount of variation possible in these respects, it seems very doubtful whether even this would be sufficient to explain the phenomenon of the advancing glaciers, and the localization of the advance in a single region. Certainly in some of the glaciers, and perhaps in all, there is no such condition as exists in the Vernagtferner, where the effect of moderate increase in snowfall is magnified when the wave of advance passes from the extensive reservoir to the small ice tongue. It would be necessary, therefore, to assume a sufficient increase in snowfall to cause the advance by its direct effect without unusual concentration. The Galiano and Atrevida glaciers, for instance, are about as broad at the lower ends of their mountain valleys as they are at their heads, above which the mountain walls rise steeply, contrasting greatly in this respect with the Vernagtferner with its broad reservoir. It would be necessary, therefore, to assume an increase in snowfall many times greater than that of the Vernagtferner reservoirs to account for equal advance of the Yakutat Bay Glaciers. Yet Black Glacier, not greatly unlike the Galiano in size, form, and supply area, and but a few kilometres from it and between the advancing Galiano and Haenke glaciers, has failed to advance. This fact is inexplicable on the basis of the hypothesis of climatic variation.

While the advance of the Vernagtferner in 1898 to 1900, as well as in earlier periods, is in important respects like that of the Yakutat Bay glaciers, it also differs in important respects. It is less intensive and spasmodic and requires a longer period to run its course; and the latter seems to be true of all advances that can be definitely assigned to climatic variations. Yet the Vernagtferner is peculiarly adapted to concentrate the energy of the thrust and to give rise to rapid, intensive response.

Although I do not find it possible to so eliminate the hypothesis of climatic variation that no one could maintain its possibility, there are so many serious objections to it that I am forced to consider it highly improbable. Under this hypothesis it is necessary to assume the interruption of a long period, during which precipitation has failed to maintain glacier ends in their position, by such a great increase in precipitation that a series of glaciers are caused to suddenly advance and as suddenly cease advancing. This assumed increase in precipitation starts a wave in glaciers of various lengths, sizes and

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reservoir conditions, and it is, so far as we know, confined to a single portion of a great mountain range that everywhere rises thousands of metres above a body of ocean water from which the prevailing winds blow. There is no proof of such climatic variation, and no known reason for its localization in the Yakutat Bay region. Were there no rational alternative explanation it might of necessity be assumed that, for some unknown reason, there came a period of unusually heavy precipitation and that, for some equally unknown reason, its effects were concentrated on this particular part of the Alaskan Coast Ranges; but even then one would be warrented in wondering, not only at the great increase in precipitation and at its localization, but also at the remarkable abruptness, intensiveness, and rapid waning of the wave of advance which swept down the glaciers, both small and large. Since there is a possible alternative theory which accounts for all the facts, and against which no fatal objections appear, there is little if any reason for retaining the improbable climatic hypothesis, which is surrounded by so many difficulties.

The Earthquake Advance Theory. The alternate theory is that the advance of the Yakutat Bay Glaciers is a response to the abrupt addition of great quantities of snow to the reservoirs of the glaciers during a period of severe earthquake shaking. The theory has the merit of being related to a known cause, for in September 1899 the Yakutat Bay region was visited by a series of earthquakes of great vigor. During a period of seventeen days, from September 3 to September 21, there was a succession of earthquakes, hundreds in all, among which several were of such vigor as to be classed as world shaking, for we find them recorded on the seismograph records of America, Europe, Asia and Africa. Two of these shocks rank, in their seismographic record, among the great earthquakes of recent times, and a third was almost of first rank. That no life was lost is due to the fact that no one lives among the shaken mountains; but the testimony of a few prospectors who were at the time encamped on the shores of Yakutat Bay, and of the inhabitants of the Indian village of Yakutat some distance away on the ocean shore, proves conclusively that the entire region was subjected to repeated shocks of great intensity, during some of which it was impossible for a man to stand up. During these earthquakes the ground was fissured in places, and in one locality a rock hill was sliced by a score or two of parallel faults with a throw of from half

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a metre to a metre. The coast line of the Yakutat Bay inlet was deformed, with some areas of subsidence, but in most parts with uplift varying from 2 to 5 metres, and in one place attaining the maximum of 14½ metres.

The descriptions of Russell and Abruzzi of the condition in the reservoir areas of glaciers descending from Mount St. Elias make it clear that the heavy snowfall in these mountains (Fig. 7) leads to a state of such instability that, even under normal conditions, great avalanches are frequently descending the steep mountain slopes to the valleys. When the mountains are so vigorously shaken that a man cannot stand up, one naturally infers that the number of avalanches would be greatly increased; and it is a well known fact that avalanching is a common phenomenon associated with earthquakes. We have abundant proof that the mountains of the Yakutat Bay region are no exception. The prospectors encamped there during the earthquakes have given us a vivid account of their thrilling experiences, and in this account the crashing sound of avalanches, in various directions, prominently figures. The native Indians, who are familiar with the shores of the Yakutat Bay inlet, assert that the face of many of the mountains was completely altered by the downfall of masses of snow and rock during the earthquakes; and we have testimony of unusual avalanching from prospectors, engineers and geologists who at the time were in other parts of the shaken area. Our own observations also prove excessive avalanching, for there are scores of fresh scars, in and near the Bay, and far more than is normal in the Alaskan mountains, basing judgment on an examination of the mountain slopes in one or two thousand kilometres of Alaskan fiords. In one case, that of the mountains enclosing the upper portion of Galiano Glacier, we had photographs taken by Russell in 1890 and 1891, and in 1905 the snow and ice conditions were noticeably different, for great masses had fallen from the mountain walls in the interval.

There can be no question but that the Yakutat Bay region was shaken vigorously and repeatedly in September 1899, and that accompanying this shaking there was extensive and unusual avalanching. Therefore the cause upon which the earthquake advance theory is based was unquestionably present. In view of the vigor and number of the earthquakes, and of the evidence of abundant avalanching, it seems fair to assume that the cause was intensely developed and that vast additions were actually made to the glacier reservoirs in a brief period of time. The earthquake advance theory makes this assumption.

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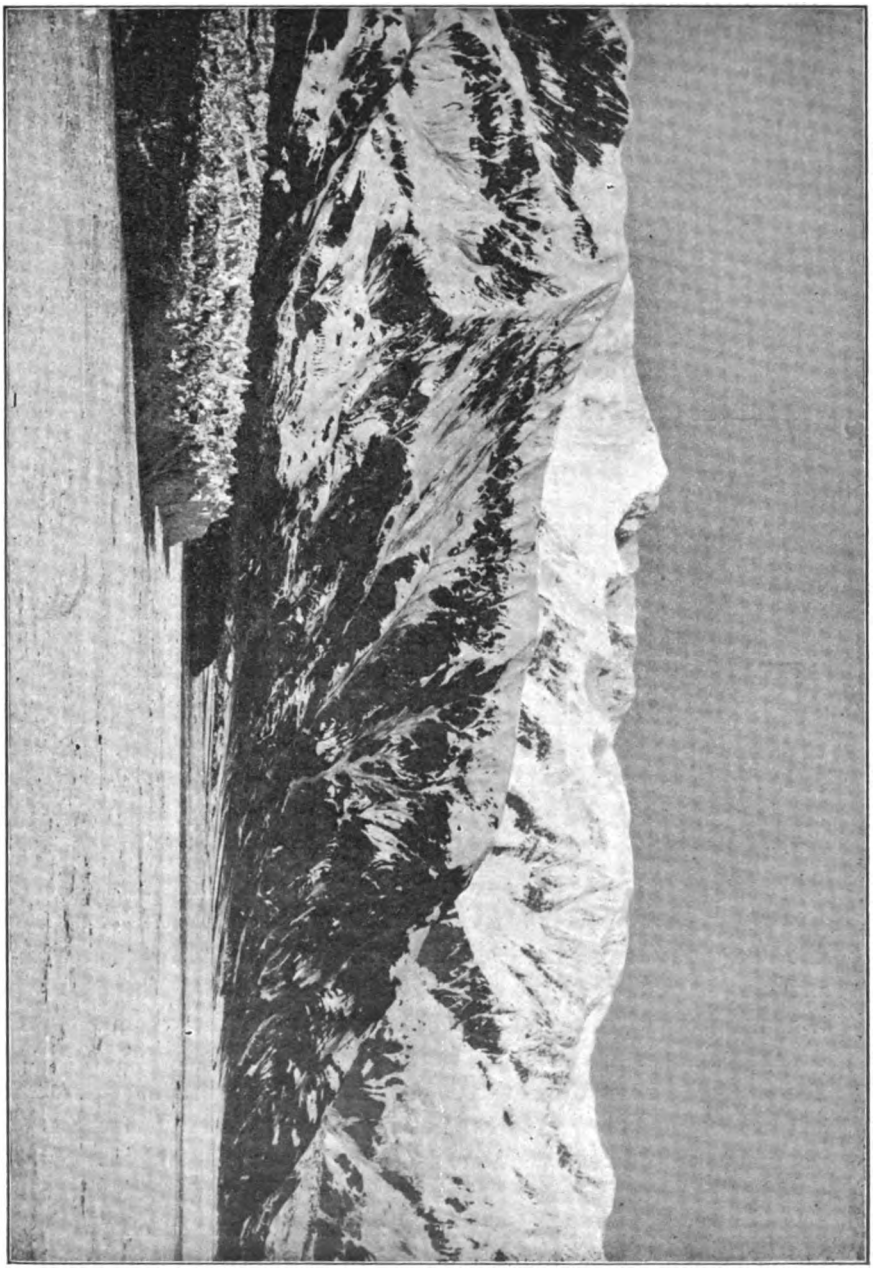

Fig. 7. View showing the heavy mantle of snow on the mountains bordering a part of Yakutat Bay, June 1906. Point of Turner Glacier, on left. Black point, just to right of it, the tidal end of Haenke Glacier, wich advanced to this position between August 1905 and early June 1906. Its former front was beyond the left margin of the photograph.

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Under this theory it is assumed that great quantities of snow, ice and rock in unstable position, that under normal conditions would find its way to the glaciers throughout a series of years, was abruptly precipitated into the glacier reservoirs, making an addition to the glacier supply both more excessive and more abrupt than would be possible under mere variation in snowfall. It is further assumed that some additions to the glacier supply were precipitated into the glacier reservoirs that never would have found their way there under normal conditions. This includes some steeply perched snow banks and glacier ends above the glacier surface, but below the snow line; and, more important than this, some of the early autumn snowfall resting on steep slopes below the snow line. By the middle of September the autumn snowfall, which is very heavy, has lowered the snow line well below that of midsummer. Normally much of this snowfall below the midsummer snow line will never find its way to the glaciers, but will be wasted by the next season's melting. By the vigorous shaking during the earthquakes, however, a part of this supply would be precipitated into the glacier valleys, especially below the reservoirs.

Such intensive addition to the glacier reservoirs as the evidence indicates, after the appropriate lag in the reservoirs, varying with the nature of the reservoir and the amount and condition of accummulation, started a wave which, gathering force, ultimately swept down the glaciers themselves, affecting the smaller, short glaciers with no expanded reservoir, like the Galiano, almost at once, but requiring several years before attaining the proper condition to sweep down the larger glaciers with more complex reservoir conditions. Because of the intensity of supply, the wave, once generated and extended to the glacier tongue, swept with great rapidity and effectiveness throughout its length, travelling 24 kilometres in less than a year in the Marvine Glacier, and nearly half that distance in less than ten months in the Variegated Glacier. A spasmodic cause gave rise to a spasmodic advance, and in harmony with the abrupt termination of the cause is the abrupt termination of the advance. In some of the larger glaciers the wave has not yet appeared, though it may yet come. In other glaciers, notably the smaller ones like the Black, no wave has come, and none is to be expected, for the time for its passage is past. Such glaciers may, for one reason or another, have escaped excessive concentration of avalanche supply in their reservoirs.

The behaviour of the waves of advance in the Yakutat Bay glaciers resembles in important respects the waves due to climatic

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variations which have swept down the Vernagtferner; but they differ in rate of progress, in intensity, in abruptness of termination, and in the absence of concentrating reservoir conditions. The great number of advancing glaciers of different length and characteristics, their concentration in a single locality, the extent of their advance, the spasmodic nature of the transformation, and the equally abrupt return to a condition of stagnation seem to demand either an increase in snowfall of such extent as to be almost impossible, or else such a spasmodic cause as the earthquake shaking theory readily supplies. With such a spasmodic cause known to be present, and with serious difficulties opposed to the climatic hypothesis, the earthquake advance theory occupies a strong position.

The theory of advance in response to addition to glacier reservoirs during severe earthquake shaking is supported by a number of facts and considerations, which may be stated as follows: — (1) There were a series of unusually vigorous earthquakes in September 1899. (2) Excessive avalanching is known to have occurred in this region during the 1899 earthquakes. (3) Both the earthquakes and the phenomena of spasmodically advancing glaciers are centered in the Yakutat Bay region. (4) Of the seven advancing glaciers, six are known to have begun their advance since 1899, and in the other case, that of Galiano Glacier, the evidence is all but conclusive that the advance was after 1899. (5) There has been a rough progression in the glacier advance from the smaller to the larger glaciers, beginning almost at once in the smallest, then affecting larger ones, then still larger, while as yet the largest have not responded. (6) The advance was spasmodic, indicating a spasmodic cause. (7) The duration of the advance was brief, indicating a cause of short duration. (8) The cessation of the advance was abrupt, indicating that the cause terminated abruptly. (9) The extent of the advance was great, involving the rapid transfer of large masses of ice in thickening, spreading, and pushing the glacier fronts forward, proving that the cause involved an intensive addition to the glacier supply. (10) The transformation is without recorded parallel, both in character and extent, which indicates the necessity of seeking an unusual cause.

While all other hypotheses either fail in vital respects, or, as in the case of the climatic hypothesis, are surrounded by serious difficulties, no facts have been observed which are opposed to the earthquake advance theory. It has the further great merit of being a cause known to have existed, and of explaining all the facts, once

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it is granted that the cause was intense enough to be adequate. It accounts for the location of the advancing glaciers in the Yakutat Bay region; for the beginning of the advance immediately after 1899 in the small glaciers; for its appearance in successive years in other glaciers; for the failure of the largest glaciers to have responded as yet; for the failure of some small glaciers to have experienced any advance; for the pronounced breaking, advance, and thickening of the glaciers; and for the sudden beginning and equally abrupt termination of the advance. Being the only theory that does not fail in some significant respects, having no vital points of objection, but on the contrary being supported by numerous facts and considerations, including our certain knowledge that, adequate or inadequate, the cause was undoubtedly present, and being competent to account for all the phenomena of the advancing glaciers, the theory of advance in response to earthquake shaking occupies a strong position, failing little, if any, short of complete demonstration.

Nature of the Movement. The passage of the advance down the Yakutat Bay glaciers, resembles closely that observed in the Vernagtferner; and the results of the thorough, careful researches on the behaviour of the latter glaciers by Finsterwalder, Blümcke and Hess[1]) are doubtless in the main applicable to the phenomena of the Yakutat Bay glaciers. Unfortunately, however, such investigations as have been conducted by these glacialists have, in the nature of the case, been impossible in the Alaskan glaciers, and it is possible to deal only with the more general features.

In attempting to understand the nature of the movement by which an impulse of the kind observed in the Yakutat Bay glaciers is transmitted down to the glacier terminus there are three facts of basal importance that must be clearly borne in mind, as follows: —

[1]) Finsterwalder, S., Der Vernagtferner, Wissenschaftliche Ergänzungshefte zur Zeitschrift des D. u. Ö. Alpenvereins, 1. Band, 1. Heft, Graz 1897. Anhang. Blümcke, A. und Heß, H., Die Nachmessungen am Vernagtferner; Blümcke, A. und Heß, H., Beobachtungen an den Gletschern des Rofentales, Mitt. des D. u. Ö. A.-V., Jahrgang 1900, Nr. 4; Einiges über den Vernagtferner, ibid. Jahrgang 1902, Nr. 18; Tiefbohrungen auf dem Hintereisferner, 1902, ibid. Jahrgang 1902, Nr. 21; Tiefbohrungen am Hintereisferner im Sommer 1908, Zeitschrift für Gletscherkunde, Band III, 1909, pp. 232—236; Tiefbohrungen am Hintereisgletscher, 1909, Ibid. Band IV, 1909, pp. 66—70; Heß, H., Zur Mechanik der Gletschervorstöße, Petermanns Geogr. Mitt., 1902, Heft V; Heß, H., Probleme der Gletscherkunde, Zeitschrift für Gletscherkunde, Band I, 1906, pp. 241—254.

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(1) The wave of advance sweeps down the glacier with great speed, as movements in glaciers go. (2) There is extensive actual transfer of material, for glacier ends advance, margins spread, and termini thicken. (3) The transfer of material occurs even in parts of the glacier hitherto quite stagnant and even motionless.

These facts make it impossible to accept as the mode of motion either the ordinary flowage of the glacier, for in that the motion is too slow, or the mere passage of a wave or impulse through the glaciers, for that does not account for the transfer of material. Thus it cannot be inferred that snow accummulated in the reservoirs and changed to ice is actually set in such rapid motion that, in a few months, there is a transfer of material from reservoir to terminus, a process which in ordinary valley glacier motion requires scores of years. Nor, on the other hand, can it be inferred that great accummulation in the reservoir starts a wave which, passing down the glacier, moves with the rapidity of wave motion breaking the ice in its passage. Any theory to satisfactorily account for the phenomena must explain both extensive actual transfer of material and rapid motion, and neither of the above hypotheses succeeds in accounting for both.

From my study of the phenomena of the advancing glaciers of Yakutat Bay, and from the consideration of the problem that I have been able to give, I have been led to an hypothesis, which I have called the *Glacier Flood hypothesis.* This hypothesis, based upon the theory of viscous flowage, assumes that the glacier ice is rigid in its upper portion and along its thin margins, but that it is in a state of viscosity beneath the rigid crust; that is, it has zones of fracture and of flowage, like the earth's crust. It is further inferred that the degree of viscosity varies with the pressure, and that with the development of viscosity the rate of ice flow is increased. The addition of great quantities of snow to the upper glacier by the effect of earthquake shaking increased the pressure in the reservoir, partly directly by the overloading, and partly by the hydrostatic pressure from heavily loaded higher portions of the reservoir. With the increased pressure, and the resulting condition of viscosity, a wave of advance was started which, applying pressure on the glacier ice in front, or down stream, induced such a degree of viscosity there that increased rate of flowage followed. This continued down the glacier, gathering force as it went, especially as the glacier narrowed or became thinner in the dissipator, and finally proceeding with

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such rapidity that it swept through several kilometres of ice in a few months, terminating only either when the glacier end was reached and pushed forward, or else when its energy was used up in thickening and broadening an expanded piedmont bulb. The rate of progress and effectiveness of the wave would vary in different glaciers according to the amount of snow avalanched into the reservoir, the nature of the reservoir, the length, width and thickness of the glacier, the grade of the glacier, the temperature of the lower ice, the amount of debris incorporated in the lower layers, and perhaps other factors. When equilibrium between overloaded upper portions and underloaded lower portions of the glacier was established by the flowage of material in the passage of the wave the advance would at once cease, because the cause for advance no longer existed.

Under the glacier flood hypothesis it is not conceived that there was actual transfer of ice from the glacier head to the glacier end within the brief period occupied by the advance, but that there was, nevertheless, actual viscous flowage of the lower ice throughout practically the entire broken area, the state of increased flowage being progressively extended down the glacier until the effects of the thrust died out. That is to say, there was a wave-like progression of a thrust down the glacier which, when applied to the ice below, induced such a degree of viscosity in the lower ice layers that rapid increase in the ice motion naturally followed. At some time during the period of wave passage the viscous lower ice of practically the entire glacier flowed forward to a greater or less distance, but no single part of the ice advanced even a considerable part of the distance from the glacier head to the glacier end. With the passage of this wave, and the accompanying viscous flowage of the lower ice, the upper rigid crust and the rigid thin margins were subjected to such strains that the glacier was broken into the impassable condition observed. The hypothesis further conceives that there was some breaking of the thin margins, both by drag and by rigid thrust, without the immediate association of viscous flowage in those thin parts of the glacier.

This hypothesis has been called the glacier flood hypothesis because of the resemblance to a river flood. When rain falls heavily, or snow melts rapidly, in the upper reaches of a river, the effect of the sudden increase in volume is extended down stream, and if the river surface is covered with ice this is broken and piled up as the rising flood passes beneath it. The phenomena of the advancing Yakutat Bay glaciers is conceived by this flood hypothesis to imitate

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the river flood in such important ways as to warrant a comparison between the two; but there are two notable differences, dependent upon the difference in liquidity of the two floods. There is first a difference in rate of progress of the flood, and secondly a difference in the nature of the flowage: the river flood involves the transfer of water from the flood source to the river mouth, while the glacier flood involves no such transfer, though the flood impulse does travel from flood source to glacier end. There are other differences of minor character, but of hardly sufficient importance for statement here. The resemblances between the two floods are numerous, including in both cases deepening of the stream, spreading at the margins, advance of the end, rising on the upstream side of obstacles (like Lucia Nunatak) breaking of the rigid crust, unusual spasmodic transformation from smooth to tumultuously broken surface, great increase in rate of motion, transfer of more material than normal, rapid subsidence after the passage of the flood wave, and perhaps other resemblances.

The glacier flood hypothesis has the great merit of satisfactorily accounting for all the facts observed in the advancing glaciers of Yakutat Bay, which is not true of other hypotheses, so far as I know them. The passage of such a wave, and the accompanying rapid flowage, readily accounts for the broken ice surface. It explains the notable thickening, the lateral spreading, and the advance of the ends of the glaciers by accounting for the transfer of the material involved in such advance, thickening and spreading. Under this theory, too, one can understand the abrupt beginning and ending of the transformation, as well the rapidity with which it progressed through the glaciers. The theory accounts equally well for the fact, observed in Lucia Glacier (Fig. 8), that the margins of the glacier were more broken than the center, as if, because of the more rapid motion in the central part of the glacier, there was either a lateral shove against the margin, or else a dragging of the margins, or possibly both combined. It accounts for the uprising of clear ice areas in the Atrevida and Variegated glaciers, just outside the mountain front where the piedmont bulb area interposed a barrier to the flood that swept down the mountain valley. In fact, there is no observed phenomenon that does not readily find explanation under this hypothesis, and for that reason I believe it occupies a strong position, certainly until some equally satisfactory theory is proposed.

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Two possible objections occur to me, and these may appeal more or less strongly to those who give the glacier flood hypothesis consideration. The first of these is the rapidity with which the wave swept through the glaciers. This objection is, however, equally strong against any other hypothesis, and it is as easy to understand the rapid passage of the wave of advance under the glacier flood hypothesis as under any other. This wave undoubtedly did pass down many kilometres of ice in a period of less than ten months, and any explanation of the advancing glaciers must assume that the cause operated as rapidly as the observed phenomena demand. If we may assume for glaciers a normal state of viscous flowage in those parts of the ice under sufficient pressure, which some will deny, it follows that increase in pressure will increase the liquidity and hence make possible a more rapid rate of flowage. The glacier flood hypothesis rests upon the assumption that the pressure from the thrust of an advancing glacier did so increase the liquidity of the ice and, moreover, that by it a sufficiently rapid rate of flowage became possible to account for the phenomena of rapid advance and accompanying thickening and breaking observed. I make no pretension of discussing the physical aspect of this subject, and, until there is fuller agreement upon the simplest principles of the behaviour of ice in moving glaciers, I feel that there would be little profit in such a discussion. The glacier flood hypothesis is put forward as an hypothesis, and therefore invites criticism; but with the present light that I have upon the subject it is the only hypothesis, so far as I know, that will explain all the facts; and if no fatal objections are proved against it, or no better, or equally satisfactory hypothesis is put forward, it may stand in spite of any supposed difficulty resulting from the observed rapid rate of progress of the wave of advance.

The second possible objection to the hypothesis, upon which, in part, the first objection rests, is really of vital and fundamental importance: namely the doubt, which some entertain, whether glacier ice does, under any conditions, behave as a viscous substance. Upon this subject opinion is divided and while some, and perhaps the majority, believe in viscosity of glacier ice under pressure, others are equally convinced of its impossibility. Much has been written on this subject both by physicists and by geologists, and since the result of this discussion has been only to lead to divided opinion, and since the results of the discussions are accessible to all, are very voluminous and varied in conclusion, and are known to students of glacial phenomena,

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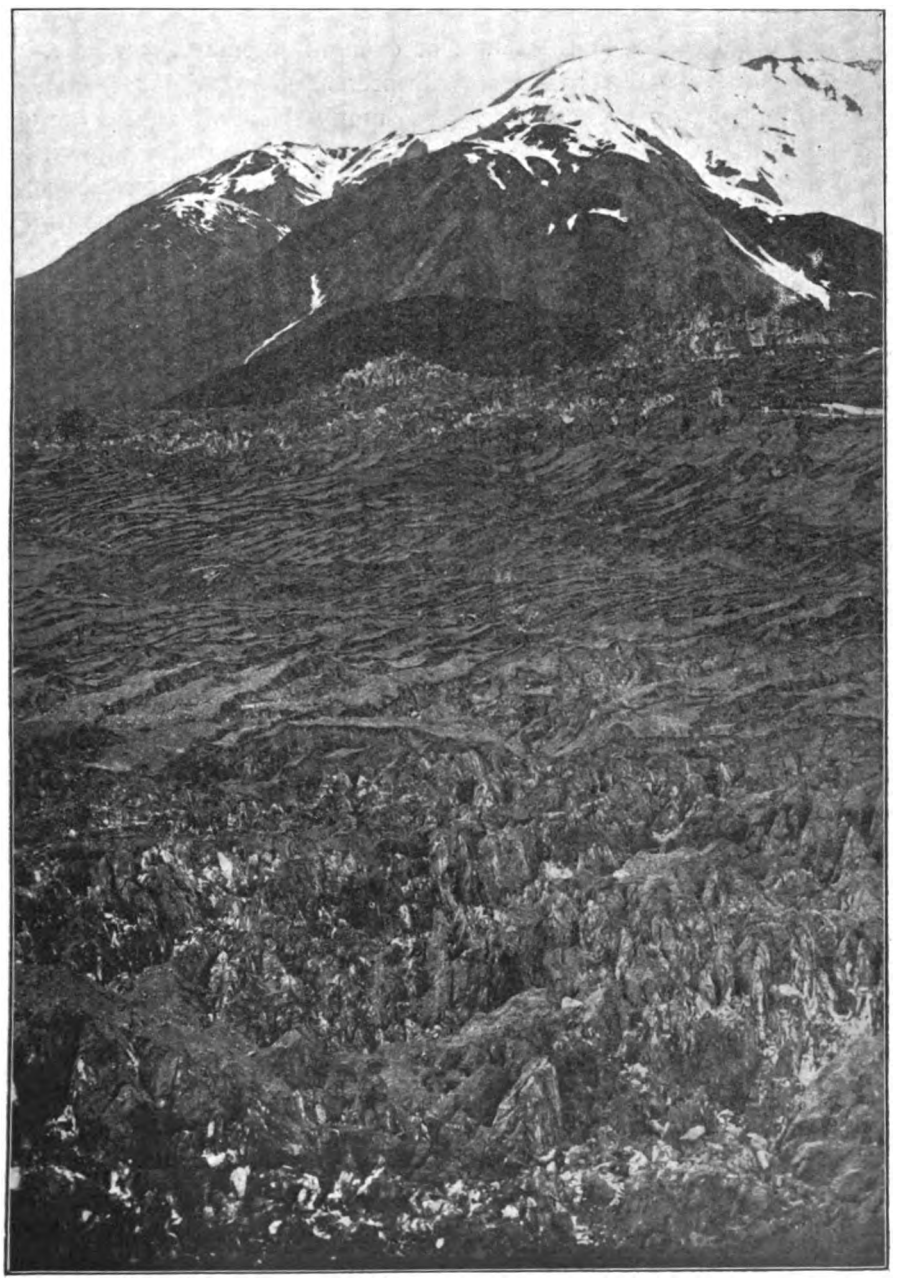

Fig. 8. The broken surface of the advancing Lucia Glacier, August 1909. Note the ice rising on the stoss (right) side of the nunatak; the long rents of the crevassed center of the glacier; and the more broken marginal portion. In 1905 and 1906 all parts of the surface were uncrevassed and easily crossed in every direction.

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it does not seem necessary to restate or even to abstract them here. The two results of importance from the present standpoint are first that, in spite of all the discussion, from many standpoints, no one has yet succeeded in so establishing any one theory of glacier motion as to convince all, and secondly that, in spite of all the attacks upon the theory of viscous flowage, it still numbers among its adherents many students of glacial phenomena.

Evidence of Viscous Flowage. From my studies of the advancing glaciers of the Yakutat Bay region, numerous facts have been observed which I am wholly unable to account for on any other theory than that of viscous flowage, either on the basis of the glacier flood hypothesis or of some modification of or substitute for it. These facts, together with a brief discussion of their significance, as I interpret it, are stated in the succeeding paragraphs as a contribution to the subject of glacier motion based upon field observation.

In less than ten months Haenke Glacier front, previously almost if not quite motionless, was pushed forward 1500 or 1600 metres, or at the rate of over 5 metres a day; and Hidden Glacier front (Fig. 4 and 5), previously stagnant and in recession, was pushed forward at a much faster rate, probably at the rate of at least 10 metres a day. In the latter case the amount of ice involved in the abrupt transfer, beyond the 1905 front, had approximately a width of over 1600 metres, a length of 3250 metres, and a depth varying from 340 metres, where the former glacier front stood, to 25 metres at the new 1909 glacier front. This is only a part of the abrupt transfer of material in the lower portion of the Hidden Glacier, for the ice was also greatly increased in depth back of where the front stood in 1905 and 1906. It is a safe estimate to make that in the lower four or five kilometres of the Hidden Glacier one or two cubic kilometres of ice was moved abruptly forward in a period of a year or thereabouts, and that some of this material moved at least three kilometres. I can conceive of no mode of glacier motion other than viscous flowage which would account for such a rapid transfer of so great a mass of ice.

The profound breaking of the surface of all the advancing glaciers is such as would normally follow rapid under-flowage of lower viscous layers, giving rise to strains and consequent crevassing in the rigid crust. Indeed, in some cases the resemblance to the behaviour of a viscous mass is remarkably close. For example, in the advancing

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Lucia Glacier (Fig. 8) the surface was rent by a series of great, long fissures, varying in direction with the direction of the glacier motion, and separated by fairly broad, table-top areas of little or no crevassing; but along the glacier margin the ice was confusedly broken, and with no apparent system. The appearance here is exactly as if a fairly rapid flowage in the deeper parts of the glacier had carried the upper rigid crust along, with only moderate and fairly systematic straining, while the thinner, more rigid margin, being dragged against the valley sides, and probably being also pushed laterally by the rising glacier flood, was greatly broken.

In the Atrevida Glacier the breaking extended far out into a stagnant piedmont bulb on which forest was growing (Fig. 9). Here the crevassing, also linear, was crescentic in form, there being a series of concentric rings of forest growth, where the ice was not broken, separated by long, regular crescentic crevasses. The appearance here was exactly like the flow lines of a slowly moving, spreading mass of some viscous substance. The breaking was not due to forward thrust and resulting fracturing, for in that case there could not have been the extensive and undisturbed inter-crevasse areas on which the forest continued to grow; the breakage was evidently due to underflowage setting up strain in a spreading piedmont area, and thereby causing crescentic rents in the rigid crust.

The phenomena of thickening of the ice masses and lateral spreading are also such as viscous flowage would produce. The thickening of glaciers, especially noticeable in the piedmont areas of the Atrevida and Variegated glaciers, had the appearance of underflowage, and, in any event, can be explained only by extensive and rapid transfer of material from higher to lower parts of the previously nearly stagnant glacier. In all cases the thickening of the advancing glaciers was accompanied by lateral spreading, closing up marginal valleys in the mountain valley sections, and elsewhere causing encroachment on lower ground. Some of the latter cases, notably the western margin of Atrevida Glacier, were so closely like the flowage of a viscous mass, such as wax, as to lead us at once to compare the two. Here the piedmont ice mass thickened greatly and flowed westward, encroaching on the territory of the still stagnant Lucia Glacier: and this spreading was in a part of the glacier hitherto stagnant. The flowage of the lower ice layers in the deeper parts of the glacier, and the associated lateral spreading, set up such a strain on the thin, rigid margins that the marginal cliffs were steepened, the

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ice was broken by thrust faults, and ice blocks were broken from the cliff and caused to fall from them. This was especially well illustrated along the advancing margins of the Atrevida and Marvine glaciers.

Still another noteworthy feature, whose explanation is clear by the theory of viscous flowage, is the fact that the advancing Lucia Glacier, on encountering the nunatak, which rises in its course, piled up on the stoss side (Fig. 8), as running water does on the upstream side of a boulder. Had the advancing Lucia Glacier been wax it would have done the same thing; if the advancing glacier is a viscous mass it would naturally thus rise on the stoss side of an obstacle. Having a rigid crust the glacier surface became greatly broken where it was piled up on the upstream side of the nunatak.

There is conclusive evidence that the thickened portions of some of the glaciers, notably Atrevida and Variegated, had much less thickness in 1909 than in 1906. A part of this reduction in thickness is due to ablation in the interval, but from our measurements of the rate of ablation this cause does not seem sufficient, by itself, to account for the whole amount of lowering of the thickened ice surface. I cannot state with absolute certainty that this is so, for we lack the necessary detailed measurements, but the evidence is all but conclusive that there has been more lowering of the surface than ablation alone can explain. In that case there must have been spreading and settling by underflowage after the advance reached its maximum. Such a charge would be quite natural and normal in a viscous body.

One very puzzling phenomenon, observed in both the Atrevida and Variegated glaciers, has a direct bearing on the mode of motion of the advancing glaciers. Since both cases are so similar, only one of them, that of the Atrevida, will be described here. In 1905 Atrevida Glacier was completely moraine-covered from well within its mountain valley out to the periphery of its piedmont bulb. In 1906 however, a large, crescentic clear-ice area appeared just outside the mountain front where the glacier surface had previously been moraine-covered. It did not attract special attention then, for it was thought to be an exceptionally broken area in which the moraine had disappeared in the crevasses. In 1909, however, when ablation had lowered the ice surface practically to the crevasse bottoms, the clear ice area still existed, and in even more noticeable condition than in 1906, with moraine-covered ice both above and below but

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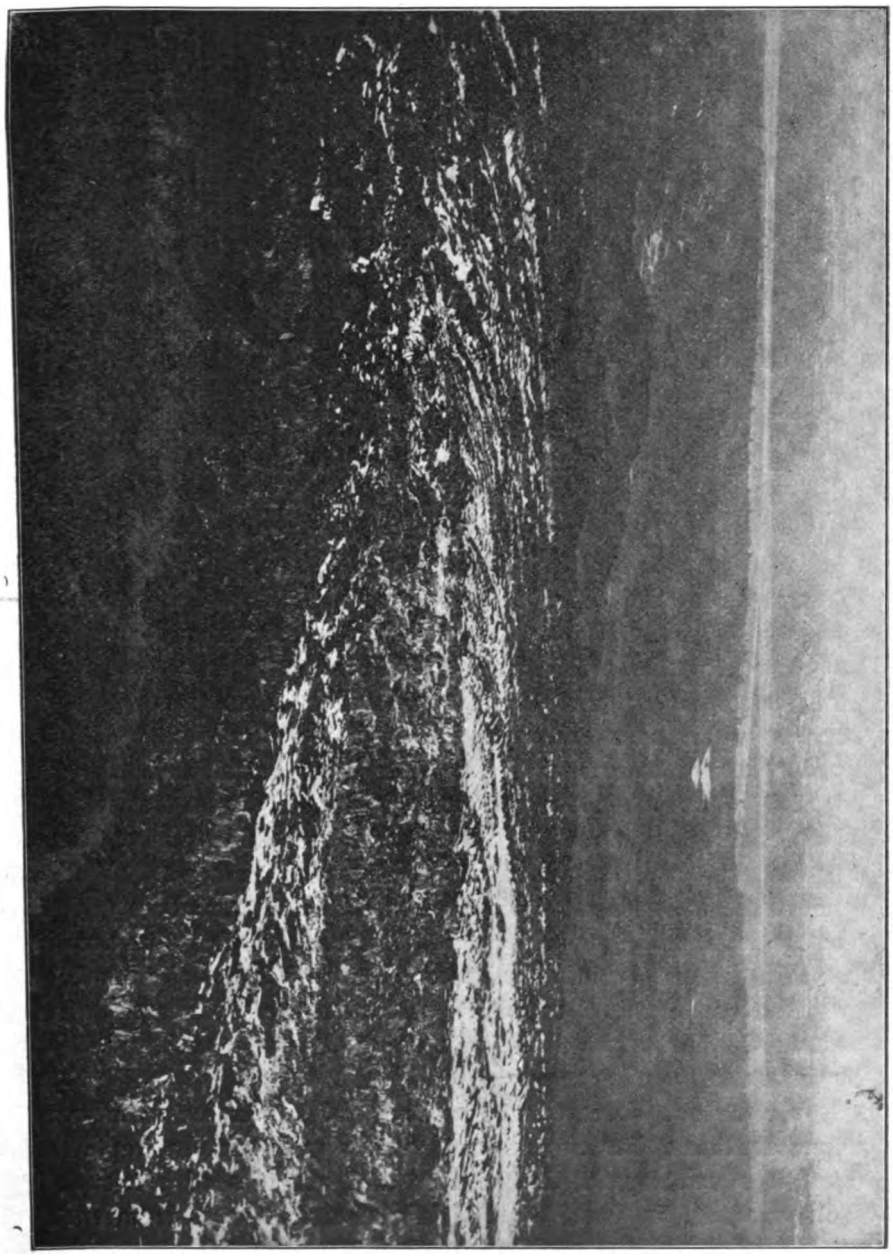

Fig. 9. The crevassed outer portion of Atrevida Glacier, June 1906. The great outer rings of crevasses are in the alder-covered portion of the piedmont bulb, where in 1905 no ice was visible.

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with absence of moraine where in 1905 there had been a continuous morainic sheet. Evidently, therefore, some change had occurred to introduce an extensive clear-ice area where moraine had previously covered the surface. In this area we observed vertical ice layers.

The only explanation of these phenomena of which I can concieve is that the underflow of the ice in the valley portion of the glacier, finding resistance in the outer, stagnant piedmont bulb obtained partial relief by rising, pushing the moraine-covered ice away. It may be stated that similar clear-ice areas are common phenomena in the Alaskan piedmont glaciers, just outside the mountain front, often forming interior flats. The phenomenon finds ready explanation on the theory of viscous flowage; but I am at a loss to explain it in any other manner.

The depth of the crevassing in the advancing Yakutat Bay glaciers is indicative of such plasticity of ice as the theory of viscous flowage demands. We have here an excellent opportunity for studying the life history of crevasses, for practically none existed before the advance, and in the portions of the glaciers free from moraine ablation has lowered the surface to or near the crevasse bottoms. The crevasses were developed in extraordinary numbers in a brief interval of time, and their cause abruptly ceased so that they have neither been continued, nor succeeded by others. The spasmodic advance and associated breaking surely gave rise to such severe straining as to cause the deepest possible breaking. Yet from 30 to 50 metres of ablation has brought the ice surfaces down to the bottom of the zone of crevasses. Had the condition of the lower ice been such as to permit, it would surely have responded, by fissuring, to the profound and abrupt straining to which it was subjected. Ice in a state of plasticity, such as the theory of viscous flowage demands, could not be fissured even by the abrupt and powerful strains which accompanied the spasmodic advance of the glaciers; but ice in a condition demanded by theories not involving a state of plasticity would be expected to yield to such sudden strains by fissuring.

We cannot observe the condition of glacier ice in motion, and experimentation has so far not even approximately duplicated the conditions existing in the interior and bottoms of glaciers. These facts account, in part, for the failure of inferences from theoretical considerations of the problem of glacier motion to bring forth results which are convincing to all. While in the Yakutat Bay region, as

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elsewhere, we cannot make direct observations on the condition of a glacier from top to bottom, we nevertheless have samples of the glacier ice, from different parts of the glacier, supplied to us for observation, in the form of innumerable icebergs floating in the waters of the fiord and stranded on its beaches. From a study of these, and of the ice cliffs of the large, rapidly moving tidal glaciers from which they come, we can form some idea of the nature of a great, active glacier from top to bottom. The largest of the glaciers, the Hubbard, presents an ice cliff of marble whiteness, about 80 or 90 metres in height, and the upper half is more or less profoundly crevassed, while the lower half is quite massive and unbroken. What lies beneath the water level is hidden from view, but the frequent appearance of icebergs black with debris, and the abundance of debris-charged bergs floating in the waters of the fiord, lead to the conclusion that the very lowest layers are heavily burdened with morainic materials.

Among the thousands of icebergs floating in the fiord, and stranded on its shores, about two thirds are whitish, and one third are glassy. This estimate is based upon several counts made in favorable localities. Some large icebergs are entirely glassy, some entirely whitish, and some have bands of white and glassy ice, the relative proportions varying in different bergs. The white bergs owe their color to the presence of great numbers of included air bubbles, all of small size, and often closely spaced; the glassy bergs have fewer air bulbs, and sometimes none at all. In general the white icebergs are the more finely crystalline, though many of them are coarsely crystalline; but the glassy bergs are always coarsely crystalline. The natural assumption is that the air bubbles of the white bergs represent air included in the course of snow accummulation in the reservoir and upper portions of the glacier, and imprisoned in the ice during its crystallization.

In undertaking to explain the difference between the whitish and glassy icebergs the fact was discovered that the difference is related to the part of the glacier from which the bergs have been derived, the glassy, coarsely crystalline icebergs coming from the lower layers of the glacier, while the more finely crystallized, air-charged bergs are derived from the upper layers. This is proved by two facts: (1) That the portion of the ice cliff above the water is white. (2) That, although a few white icebergs were found which contained some debris; the most heavily debris-charged bergs were invariably glassy. That

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all the glassy icebergs do not contain debris, may be assumed as proof that the glassy condition extends some distance above those basal layers which are heavily charged with debris; and the fact that some whitish bergs contain debris is readily explained by the presence of some debris in the glacier above the bottom, and especially in the areas of medial and lateral moraines.

From these facts I reach the conclusion that in such a glacier as the active Hubbard, whose rapidly moving front is truncated by the discharge of icebergs, there is a change in character of the glacier ice from top to bottom, first in crevassing, and secondly, in the abundance of included air bubbles. The upper layers are prevailingly white and crevassed, the lower layers glassy and uncrevassed. There is some reason for believing that there is also a change in coarseness of crystallization, but on this point the observations are not conclusive. It may be well to add that this change in condition from white to glassy would not be expected in those glaciers ending on the land, in which ablation had so greatly lowered the surface as to remove the upper whitish layers.

Having determined the position of the glassy ice in the glacier the question naturally arises, why is the glacier charged with air bubbles in its upper layers, while there is no such abundance of included air in the lower ice? It is inconceivable that the lower ice originally contained less imprisoned air than the upper ice, for it is from the same source of snowfall in the upper glacier, compacted and consolidated into the crystalline ice rock. The conclusion is forced upon us, therefore, that in some way air originally included in the lower zone of glassy ice has been eliminated in the course of development of the coarsely crystalline structure. That such elimination is in progress in the ice is indicated by the fact that air bubbles are present in varying quantities in some of the coarsely crystalline icebergs, and in all finely crystalline bergs, while in the very bottom layers, which are heavily debris-charged, there is almost complete absence of included air. These facts seem to force the conclusion that in some parts of such a great glacier as the Hubbard there are conditions which permit the elimination of included air bubbles, and that these conditions prevail mainly, if not entirely, in the bottom layers of the glacier.

The elimination of air from the lower glassy layers is in harmony with the theory of viscous flowage, though it is possible that it might be explained on the basis of other hypotheses also. Assuming a state

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of viscosity in deep, rapidly moving glaciers, I propose the following hypothesis to account for the development of the lower layers of glassy, coarsely crystalline ice. When under sufficient pressure to flow with the rapid rate of the Hubbard Glacier, the lower portion of the glacier is in a condition of sufficient liquidity to force the escape of a large part, and in places even all, of the included air bubbles, which, rising, become included in the upper layers of viscosity, giving rise to those layers of ice from which the whitest icebergs are derived. Whether the coarsely crystalline structure is present in the viscous ice, or whether it develops as the front of the glacier is neared, and the pressure relieved, is not indicated by any facts which I have observed.

From the above statement of facts, and from the consideration of the inferences which seem to be warranted by these facts, I am led, from various points of view, to the same result, and am wholly unable to unterstand the phenomena observed in the Yakutat Bay region without resort to the theory of viscous flowage. By this theory all phenomena are readily explained, while by any other theory I find myself confronted by grave difficulties in accounting for the phenomena. I am, therefore, forced to believe that the theory of viscous ice motion has foundation, and that the phenomena of the advancing glaciers of Yakutat Bay are an expression of an unsually active phase of such flowage.

The theory of viscous flowage of glacier ice has lost favor with some students of glacial motion by reason of certain facts and considerations, such as the fact and condition of crystallization of the ice, the evidence of the great erosive power of moving ice, and certain phenomena of faulting and crevassing observed along glacier margins; and the inference has been drawn that these conditions are incompatable with a condition of viscosity. In this, as in other studies of the problem of glacier motion, the development of theory has been under the serious disadvantage that critical facts have been unknown, and that assumption has therefore been necessary, which, if incorrect, removes the foundations of the theory. All theories of glacial motion involve certain assumptions upon which there is not general agreement, — hence the failure of even the most elaborately argued theories to receive universal acceptance. This is true, for instance, of what is, perhaps, the chief rival theory to that of viscous flowage, — the theory of alternate melting and freezing, under a complex process of application of pressure and release of pressure, with the development

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of temporary local fluidity by which forward, downgrade motion becomes possible. There is by no means general agreement that the fact that ice is a crystalline rock, and that it is a powerful agent of erosion, are incompatable with a condition of viscosity. In fact, the latter point seems to some more easily explained by viscous flowage than by any other hypothesis. There is even less reason to agree with the assumption that crevassing, thrust faulting, sliding of layer on layer, and other observed phenomena of glacier margins and surfaces are opposed to viscosity; for those who accept the theory of viscous flowage as rational distinguish between viscous lower ice layers, under pressure, and rigid upper crust and thin margins which, being under little or almost no pressure, normally yield to strains by breakage, not by the flowage characteristic of the lower ice layers.

Passing over the question of basal assumptions, however, and applying the theory of melting and freezing to the advancing glaciers of Yakutat Bay, it seems wholly incompetent to explain the facts. To assume that melting of ice under pressure of crystal against crystal, has given rise to sufficient water for the passage of the great wave of advance through 24 kilometres of ice in the Marvine and Malaspina glaciers, and about half that distance in the hitherto stagnant Variegated Glacier, all in a period of less than a year, strains the imagination. Even more difficult is the conception of the operation of this process in supplying the ice necessary to thicken the piedmont bulbs of Atrevida and Variegated Glaciers, and to thrust Haenke Glacier front forward 1½ kilometres, and Hidden Glacier front 3¼ kilometres, in a similarly brief period of time.

As already stated, however, it is not the purpose of this paper to undertake a discussion of the extensive and complicated literature of glacial motion, nor even to attempt a critical consideration of rival hypothesis, as applied to the explanation of the phenomena of the advancing glaciers of Yakutat Bay. My purpose is to briefly state some of the facts observed in the field, and in explanation of them to propose certain hypotheses which, from such consideration of the subject as I have been able to give, seem to me the most rational explanation of the phenomena, and opposed to which I have been able to find no fatal objections. Viscous flowage of lower ice layers under pressure forms an essential part of the explanation proposed to account for the phenomena of the advancing glaciers. If any other mode of ice motion can be proved to be competent to

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account for these phenomena, then the hypothesis of viscous flowage will not be so necessary as it now seems to me to be. I do not consider, however, that such arguments as have hitherto been advanced against the theory of viscosity of glacier ice have sufficient force to render its introduction as a part of the glacier flood hypothesis unwarranted, especially in view of the apparent need of it in explaining some of the phenomena observed. If this apparent need is real, as I believe, then the phenomena exhibited by the advancing glaciers of Yakutat Bay have contributed facts of basal importance in understanding the nature of glacier motion both here and elsewhere. It is my belief that this is the case, and I therefore present the facts, with inferences based upon them, for the consideration of students of glacier motion.

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